The Rocky 7 Rover: A Mars Sciencecraft Prototype

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ABSTRACT

This paper describes the design and implementation at the Jet Propulsion Laboratory of a small rover for future Mars missions requiring long traverses and rover-based science experiments. The small rover prototype, called Rocky 7, is capable of long traverses, autonomous navigation, and science instrument control. This rover carries three science instruments, and can be commanded from any computer platform from any location using the World Wide Web. In this paper we describe the mobility system, the sampling system, the sensor suite, navigation and control, onboard science instruments, and the ground command and control system. We also present key accomplishments of a recent field test of Rocky 7 in the Mojave Desert in California.

1. INTRODUCTION

Even prior to the recent discovery of the possibility of past life on Mars by a research team of scientists at the Johnson Space Center and at Stanford University, NASA had planned six missions to Mars for 2001, 2003, and 2005. Currently, NASA is updating its Mars exploration plans to develop strategies that lead to one or more sample return missions. Since samples must be examined using onboard science instruments and collected from a variety of sites, rovers will play a crucial role in these missions. These rovers will traverse to sites separated by several kilometers and place instruments against outcrops or loose rocks, search an area for a sample of interest, and collect rocks and soil samples for return to Earth. Our research objectives are to develop technologies that enable such scenarios within the mission constraints of mass, power, volume, and cost.

Scientists [1] have three main objectives in exploring Mars: to search for evidence of past or present life, to better understand the climate history of the planet, and to determine what resources it provides for future explorations. These objectives can be addressed by performing remote experiments on the atmosphere and on the soil and the rocks on the planet and by detailed examination of samples returned to Earth from Mars. Stationary landers [2] will provide excellent scientific data characterizing the atmosphere and the soil, resulting in information on the climatic history of the planet. Both the atmosphere and soil are likely to be well mixed and accessible at most sites and to be efficiently characterized without significant mobility. However, the atmosphere and the soil have serious drawbacks for understanding long term climatic and biologic issues. In contrast, the rock record is one of discrete events whose time sequence can be reconstructed.

To enable such remote experiments, scientific data must be obtained from the soil, atmosphere and rocks in an area near the landing site. Due to the lack of high resolution orbital images and the landing error ellipse, it is highly desirable that mobile systems be used to reach different areas to conduct scientific experiments. For sample return missions, a mobile rover can collect a small number of rock and soil samples from different areas for the returning spacecraft.

The Mars Pathfinder Rover called Sojourner [3] represents the state of the art in flight microrovers today. This rover was launched on December 4, 1996 and will arrive on Mars on July 4, 1997. Sojourner is the first rover to be deployed on Mars and will provide valuable data for the design of future, more capable rovers. Sojourner has a very limited range (tens of meters), is not capable of sample acquisition and manipulation (i.e., soil and rock acquisition, subsurface access, pointing and burial of instruments), has limited science packages onboard, is designed for short term missions (the nominal mission is less than a month), and requires careful and repetitive ground monitoring and control (i.e., it has limited autonomy).

Our goal is to develop technologies that overcome the limitations detailed above as well as to introduce new capabilities currently not supported. These are:

- Increasing rover autonomy so that the number of science experiments per uplink command is increased, resulting in more science data. This involves increased autonomy for rover navigation so as to reach science targets, autonomous confirmation of reaching such targets, and use of sensory information to perform autonomous manipulation and science instrument placement and pointing.
- Developing the ability of the microrover to traverse long distances by (a) integrating a celestial sensor (e.g., a sun sensor) to determine the rover's orientation and (b) developing a deployable mast mounted camera system to send panoramic images of the surrounding area to the ground control personnel.
- Integrating representative science instruments onto the rover and developing intelligent data reduction techniques to maximize the useful science return.
- Developing onboard resource analysis and decision making capability so that maximum science is returned for the available resources.
- Developing a distributed Internet-based rover interface so that scientists can make science experiment requests and the general public can view return images immediately.
- Testing and validating these technologies in realistic settings and with planetary scientist participation.

This paper provides an overview of our prototype rover called Rocky 7. Section 2 gives a description of the mobility system, the sampling arm, sensors, the perception system, the navigation technique, and the science instruments. Section 3 describes a new operator interface development that allows a rover to be commanded from any location using the World Wide Web. Section 4 describes the highlights of a recent field test of Rocky 7 rover. Conclusions are given in Section 5. References are provided in Section 6.

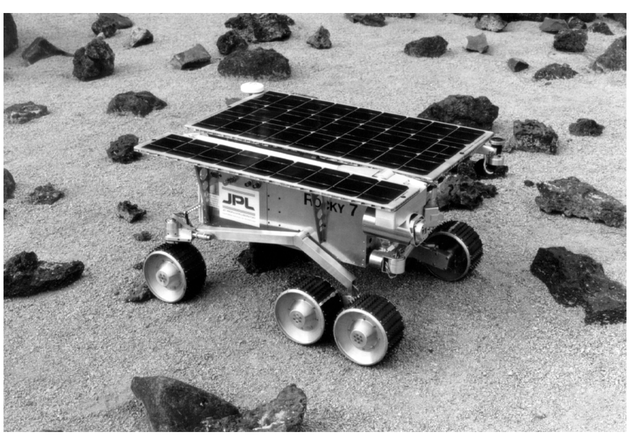

Figure 1. Rocky 7 Rover in JPL Mars Yard shown with stowed mast and sampling arm.

2. THE ROCKY 7 ROVER

In this section we provide the Rocky 7 rover configuration, and we detail the constituent components. Figure 1 shows Rocky 7 in the JPL Mars Yard. The Mars Yard is a 15 X 25 meter outdoor test area that closely simulates Mars-like terrain constructed on the basis of statistical analysis of images taken by Viking Landers I and II.

One important consideration in developing Rocky 7 has been its flight relevance. This has severely constrained its size, mass, and power. The size of the rover is dictated by the size of the payload envisioned for future missions. Rocky 7 measures 48 cm wide, 64 cm long, and 32 cm high. The wheel diameter is 13 cm. The peak power available on Mars using a solar panel is 15 watts. Since commercial components are used on Rocky 7, its current power consumption is higher than 15 watts, but there are flight equivalent components that can reduce the power required to 15 watts.

2.1 The Mobility System

The mobility system is a modification of the Rocker-Bogie design used in previous rovers at JPL [4]. It consists of two rockers (hence the name "Rocky") hinged to the sides of the main body. Each rocker has a steerable wheel at one end and a smaller rocker at the other end. Two wheels are attached to the end of each of these small rockers. The main rockers are constrained in motion via a lever which is hinged at the end of the main body and whose two ends are attached to the end of the main rockers. This mechanism provides an important mobility characteristic of the rover: one wheel can be lifted vertically while other wheels remain in contact with the ground. This feature provides rock climbing capability for the rover. Rocky 7 can climb rocks 1.5 times its wheel diameter in height.

Unlike its predecessors Rocky 3 and 4 (and the Sojourner flight rover) that have four steerable wheels, Rocky 7 has only two. This configuration has been selected to reduce the number of actuators used for rover mobility from 10 to 8, with an option to reduce it further to 6 (the two wheels on each small rocker can be mechanically linked to each other). Although this restricts the rover's turning capability, i.e., the rover cannot turn exactly in place, Rocky 7's ability to navigate forward and backward reduces the need for turning-in-place moves.

2.2 The Sampling System

One significant improvement over previous Rocky series rovers is the incorporation of a sampling device on Rocky

7. The savings in actuators achieved by reducing the number of steerable wheels has been used to develop the sampling system. This lightweight (650 gm) sampling arm consists of a two-DOF manipulator (32 cm long) that is attached to the front of the rover and can reach 10 cm below the ground surface. When folded, it is in a horizontal position against the front of the rover. The arm has a two-DOF scoop mechanism that is designed both to dig and carry the samples. When the scoops are rotated 180 degrees backward, the arm can grasp objects by using the back side of the scoops [5]. Figure 2 shows the sampling arm with an acquired soil sample.

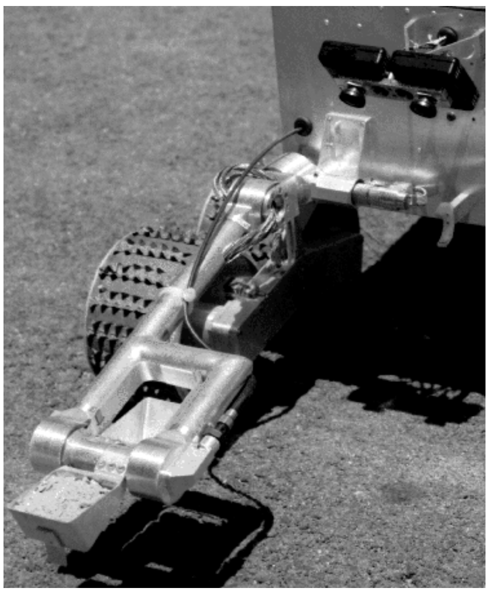

Figure 2. Sampling arm of Rocky 7 Rover

In addition to its sampling function, the arm is used to deliver light to an optical fiber via a pair of mirrors. This is accomplished by configuring the scoops to a position and exposing a normally closed hole. The optical fiber carries the light (image) to a point spectrometer located inside the rover chassis (see Section 2.6).

The arm can be deployed for three different operations: digging, dumping, and spectrometer data acquisition. Before each deployment, the rover checks for possible collision of the arm with obstacles (rocks) by using its onboard stereo vision system and automatically positions itself to avoid them. For a dig operation, the vision system also processes the images of the area in front of the rover to determine if the ground is soil-like by analyzing the image texture and elevation information. It then deploys the arm and lowers it until contact is made with the surface by monitoring the arm motor current. After the dig operation, it positions the scoop that collected the sample and takes its image. The rover then compares this image against the one taken just before the dig operation. If it detects enough difference between these two images, the rover reports success and completes the dig operation by closing the scoops and stowing the arm. Otherwise it does an automatic dump, stows the arm, and reports failure. Similar autonomous checks are performed for a dump operation.

2.3 Sensors

Several sensors are used for navigation. A sun sensor developed by Lockheed Martin, called the Wide Angle Sun Sensor (WASS), with a 160 deg field-of-view provides heading information. This information is computed onboard based on the rover's location, its pitch and roll, and the time of day. This sensor is critical for rovers that must traverse long distances in a specified direction. Figure 3 shows the sun sensor which is mounted on the solar panel of Rocky 7.

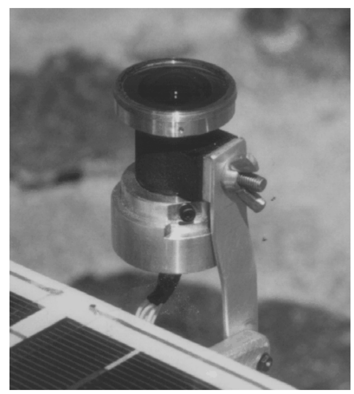

Figure 3. Wide angle sun sensor

A rate gyro is also available and can be utilized when the sun sensor signal is weak. Due to the drift rate of the gyro, it must periodically be reinitialized by using the sun sensor. In addition, an accelerometer is installed to provide pitch and roll information. This information is used by the sun sensor and the perception system to account for the rover's pitch and roll. The wheels are equipped with encoders for precise servo control and to estimate the rover's position. The position of the front lever and the small rockers is sensed by potentiometers and can be used for the rover's state estimation. The rover is equipped with seven CCD cameras, two at each end, for the perception system and three on the mast (see Section 2.5).

2.4 The Perception System

To simplify the perception system hardware, Rocky 7 uses passive stereo vision [6] for hazard detection, unlike its predecessor, which used a laser striping system in conjunction with multiple monocular cameras to detect obstacles. The stereo vision system uses a pair of cameras with wide angle lenses to allow viewing of both the manipulator and its actions, as well as to permit imaging of rocks and other hazards extending from near the rover to a little above the horizontal.

A pair of frame grabbers is used to obtain two 256 X 240 images. These images are warped to remove radial distortion and then reduced to 64 X 60 images by an image pyramid transformation. The Laplacian-transform of-Gaussian images from the pyramid are processed onboard by a correlation algorithm to develop a stereo disparity estimate which is transformed by means of a camera model to a range map.

Using this map, a decision is made as to the presence or absence of "step" hazards that are too steep for the rover to climb over, or of "high-centering" hazards that could cause the rover body to get stuck on a rock. In the current implementation, which has not been streamlined for speed, it take 4 seconds using an onboard 68060 CPU to process one pair of images and determine whether or not there is a hazard in the near vicinity of the rover.

One important advantage of using passive stereo vision based perception is that the information obtained is based on higher resolution image processing than that of the laser striping system. This allows for detection of rocks with shapes that could cause them to be missed by a laser striping system. There are also possible disadvantages to the stereo vision based perception system, since featureless objects such as sand dunes or "bland" rock walls may not be detected. A combination of a passive and an active perception system might be the optimal choice.

Another advantage of the stereo vision system is that it is easy to extend the system capability by adding cameras to the back side of the rover and other cameras using the existing infrastructure (i.e., frame grabbers and software).

2.5 The Navigation System

The Rocky 7 navigation strategy is based on operator waypoint designation and autonomous behavior based navigation for movement to the specified targets [7, 8]. Two modes of operation are possible.

1- Lander-based navigation: This is the mode where the rover is in the field of view of the lander. The operation starts with a command to the lander, which has a pan-tilt mounted pair of stereo cameras to take a panoramic image of the scene by obtaining several overlapping images. These images are then processed by stereo vision software to obtain terrain maps on Earth. Interactive software allows one to select specific points (locations) on one of these images by using a mouse. The software returns the position of this location as calculated by the stereo vision system and displays the coordinates of the point. The operator continues this operation and builds a path which he or she deems to be safe for the rover to traverse in moving from its initial position to the target location.

2- Landerless navigation: When the rover is no longer close to the lander, it is commanded to raise its three DOF mast and acquire panoramic images. The mast when deployed stands 1.4 m above the ground. This mast weighs only 700 grams and has been designed to be stowed when not in use to minimize the duration when it casts shadow on the solar panel. This mast also is used for pointing and placement of science instruments and rover self-inspection. The shoulder roll joint is used to take panoramic images. The shoulder and elbow pitch joints provide the tilt angle for the panoramic images. These images are then sent to the ground station and processed. Waypoint designation is carried out and a path is defined.

The scenario for long range traverse consists of moving in the indicated direction, using the sun sensor, and periodically (e.g., ~100m to 200 m) transmitting panoramic images to the ground station. The ground station will provide new commands to either continue to traverse in the same direction or change direction. If the site is of interest to scientists, the site survey commands is issued.

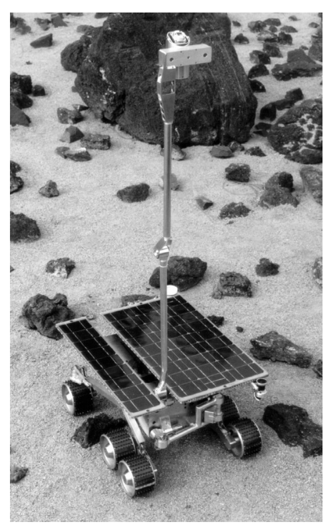

Figure 4. Rocky 7 shown with deployed mast

Before each move, the rover takes a set of images, processes them onboard and determines if there are obstacles that it must avoid. If there is no obstacle, it moves a short distance and then stops and repeats the same operation. If it determines that there is an obstacle, it turns away by a fixed amount to the right or to the left, depending on where the obstacle is. The rover uses its odometry and the sun sensor (or the rate gyro) to update its position. When the way is clear, the rover plans a path that takes it to the original waypoint. In order to stay away from the obstacle, this path is constructed to be an arc of a large radius. If the rover turns away from an obstacle and then detects another obstacle (or the same one), it keeps turning away until it does not detect any obstacles. The rover then plans a path to the waypoint as described before. However, if the rover turns 360 degrees and does not find a collision-free path, it gives up and sends a message to the operator.

2.6 Rover Localization

For increased autonomy, it is essential to update the rover's position as the rover moves to various target locations without assistance from Earth. The rover's positional information loses accuracy rapidly due to wheel slippage and sensor measurement errors. The orientation accuracy, however, remains high due to the use of the sun sensor.

For lander-based operations, we have developed autonomous lander-assisted rover localization that updates the position of the rover relative to the lander.

When the rover is commanded to perform an automated localization, it first reports its best estimated position to the lander by using dead-reckoning. The lander then "looks" at the rover by using its pan and tilt mechanism. Since the lander is equipped with wide-field-of-view lenses, it is likely that the rover will be within the field of view. The lander takes a set of images using its stereo cameras. The rover then turns by a small angle, and the lander takes another set of images. The lander then processes these images by first performing an image differencing and then a triangulation of the difference. The lander then computes the rover's position and performs checks to ensure that the data are valid. The lander then commands the rover to update its position using the new x and y values. Tests have shown that this localization is accurate to within 85%.

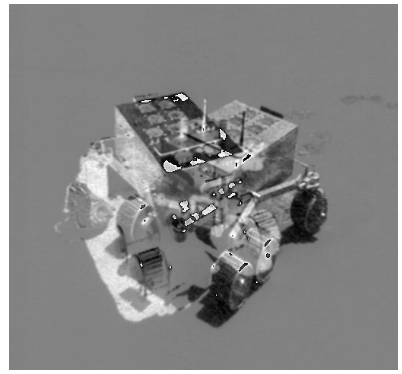

Figure 5. Image differencing for rover localization

This technique cannot be used for landerless operations. Research is under way to achieve self-localization in a natural terrain by comparing a dense range map computed from stereo imagery to a range map in a known frame of reference [9].

2.7 Science Instruments

An important objective of our research in developing rovers is to understand not only the mobility, navigation, and control issues, but also to consider problems associated with the integration of science instruments, and their onboard operation and data reduction. Currently, Rocky 7 has three science instruments: a point reflectance spectrometer, a wide field of view spectral imager, and a close-up spectral imager.

The point reflectance spectrometer is on board the rover chassis, and its fiber optic path is integrated into the rover manipulator. This allows the spectrometer to be pointed at rock/soil targets from many different angles. Also included on the manipulator is a calibration target for taking reference data for the current illumination. The spectrometer has a range of ~400-850 nm, which is useful for looking for spectra of different minerals. Onboard software has been developed that matches spectral signatures. This capability can be used by the rover to find targets autonomously.

The wide field of view spectral imager has been developed by adding motorized filter wheels to the mast cameras. This filter wheel system is used to gather broadband spectral data, enabling color images to be constructed. The mast is a three degrees of freedom torso/shoulder/elbow articulated robotic arm enabling the cameras on the end to be positioned 1.4 meters above the ground as well as to pan and tilt to get the desired imagery. The cameras are shown in Figure 6.

The third instrument is a close-up imager that uses a monochrome camera and an active lighting source. This is packaged as a 500g "dummy" instrument representing an APX or Moessbauer spectrometer which would have to be placed against a designated target. The instrument is mounted at the end of the mast, and the mast degrees of freedom are utilized to position the instrument against rocks in front of the rover. Passive compliance is used to allow the instrument to orient itself normal to the target surface, and contact sensors are used to confirm placement.

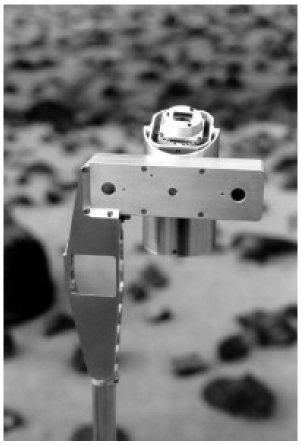

Figure 6. Spectral and Close-up imagers.

3. The Advanced Operator Interface

We have developed a ground control station to command the rover remotely and receive data from it. The operational scenario is based on the rover down-linking science data and stereo panoramic image pairs. These data along with camera parameter information are used to develop terrain maps.

The interface is Web based and consists of viewing an image taken by a rover camera. An operator can point to and click on any point on the image and obtain the coordinates of the point. This interface allows a scientist to select science targets from his or her home institution by using any computer platform. He/she is also able to describe the nature of a particular science experiment to be performed at that point (the pointing requirements, time required for data collection, data compression, etc.). This information is then sent electronically to a central station at JPL for consolidation and verification of flight rules, in preparation for next day's mission and for uplinking to the rover [10]. Figure 7 shows the interface for remote target and waypoint selection. The image on the right shows the waypoints selected. The image on the left shows a top view of the elevation map generated from panoramic images. The right-side image corresponds to one of the wedges shown in the left-side image.

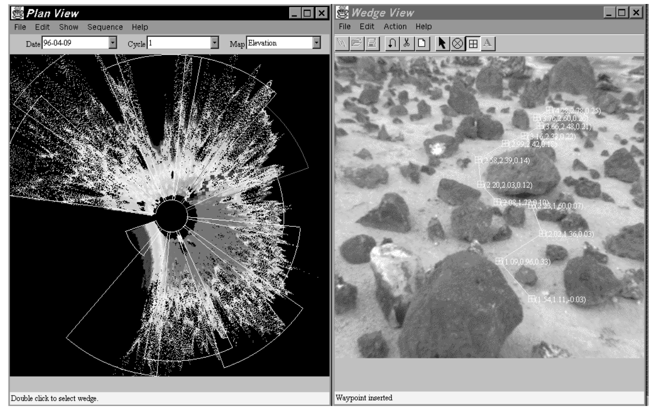

Figure 7. Web based operator interface.

4. Field Testing of the Rocky 7 Rover

In order to understand the performance of the Rocky 7 Rover in a Mars like terrain, several field tests have been planned. These field tests are collaborative activities between the Rocky 7 research team and several planetary scientists selected from NASA and various universities. The first field test was undertaken in the Mojave Desert in California in December of 1996. The objectives were to:

1- Traverse 200 m using the landerless mode of operation, i.e., by taking panoramic images and planning paths based on these images
2- Acquire soil samples
3- Place the close-up imager on scientist specified rocks
4- Perform rover self-inspection
5- Take science images by using the mast and the rover navigation cameras
6- Perform operations from remote locations

The rover performed all of these operation successfully in a three-day test. The joint team of scientists and engineers is currently compiling the results on a web page dedicated to Rocky 7 field testing [11].

Figure 8 shows the rover performing close-up imaging of a rock. This operation requires autonomous positioning of the rover in the vicinity of the rock, which is selected by scientists from images sent by the rover. The rover turns and moves forward and positions itself close to the rock. It then confirms that the rock is the one that was selected by using rock's location and height as measured by the rover. The rover then computes the mast trajectory to place the mast on the designated point on the rock. The motion of the mast is stopped when sensors at the mast's tip indicate that contact has been made. After this operation, the rover starts its imaging operation and takes several images by using different

LEDs on the close-up imager. (See Ref. 12 for more information and images.)

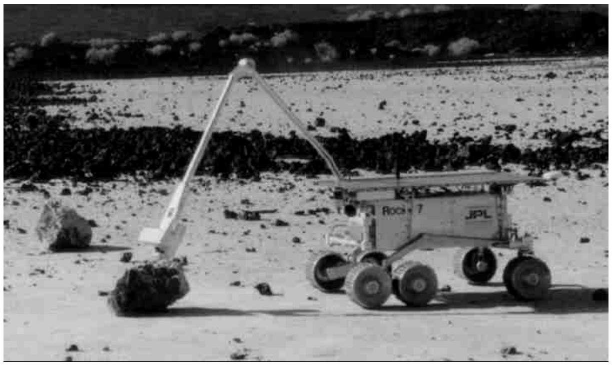

Figure 8. Spectral and Close-up imagers.

5. CONCLUSIONS

This paper has provided an overview of research on future Mars rovers, covering navigation, perception, science instrument pointing and placement, and operator interface issues. It has also provided preliminary information on the key accomplishments of a recent field test of the Rocky 7 rover. The Rocky 7 rover will be field tested in May of 1997; it will use two new science instruments and will traverse 1-2 km. The rover will be operated remotely and simultaneously from several locations within the United States.

Although this research program covers many essential elements of Mars rovers, research related to materials, space qualified computers, communication hardware, thermal insulation, advanced mobility systems, and structures are being address by other tasks at JPL [13].

ACKNOWLEDGMENTS

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